U.S. DEPARTMENT OF ENERGY | Nuclear Energy

Advanced Reactor Concepts Research and Development

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Advanced Reactor Concepts (ARC)

The mission is to develop and refine future reactor concepts that could dramatically improve nuclear energy performance (e.g., sustainability, economics, safety, proliferation resistance, and minor actinide burning)

The strategic approach is to:

- **Tackle key R&D needs for promising concepts**
  - *Fast reactors for fuel cycle missions*
  - *Fluoride salt cooled thermal reactor for high-temperature missions*
- **Develop innovative technology features with potential benefits to many concepts**
- **Utilize international collaborations to leverage and expand R&D investments**
  - *Continuation of Generation-IV R&D Projects*
  - *Investment in strategic bilateral or trilateral partnerships*

Introduction

Four main focus areas for ARC Research

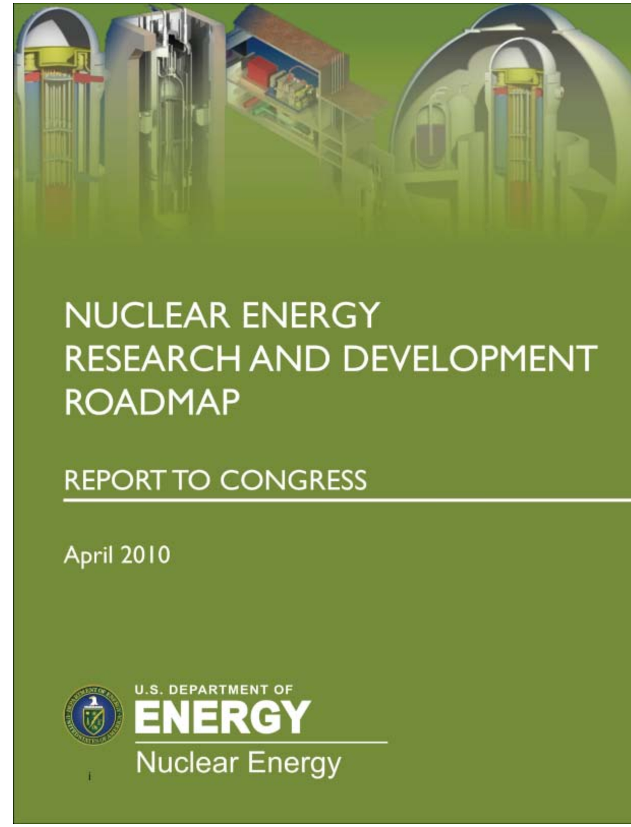
- **Fast Reactors, principally Sodium Fast Reactors (SFR)**
- **Fluoride Salt-Cooled Reactors (FHR)**
- **Super-critical CO_2 Brayton cycle generators**
- **International Programs**

ARC-AFR Objective(s) and Needs

- ***ARC-AFR Objective - Develop advanced fast reactor technology solutions to allow commercial deployment by 2050 timeframe***

- ***Supports multiple Objectives identified in the Nuclear Energy R&D Roadmap (2 & 3)***
  - *(2) Develop improvements in the affordability of new reactors to enable nuclear energy to help meet the Administration's energy security and climate change goals*
  - *(3) Develop sustainable nuclear fuel cycles*

    "The overall goal is to have demonstrated the technologies necessary to allow commercial deployment of solution(s) for the sustainable management of used nuclear fuel that is safe, economic, and secure and widely acceptable to American society by 2050."

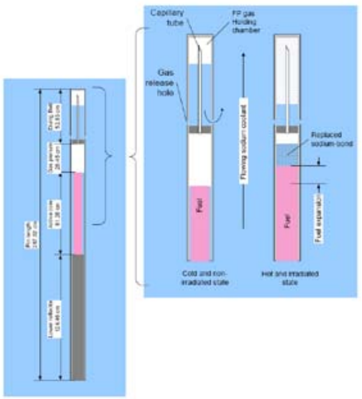


Fuel Cycle Mission: Fast Spectrum Reactors

- **For closed fuel cycle options, must develop and demonstrate recycle reactor technology**
  - Significant waste management and resource extension benefits
  - Fast reactor needed for final transmutation system
- **For future fast reactor technology, the key <u>research focus is capital cost reduction</u> (i.e., major commodity reductions or efficient electricity generation) through**
  - Improved design approach (e.g., compact configuration)
  - Advanced technologies (e.g., materials, energy conversion)
  - Advanced simulation for optimized design
- **A second research focus is assurance of safety to promote design simplification and licensing**
- **A third, related focus is high system reliability**

Fast Reactor Advanced Concept Studies (examples)

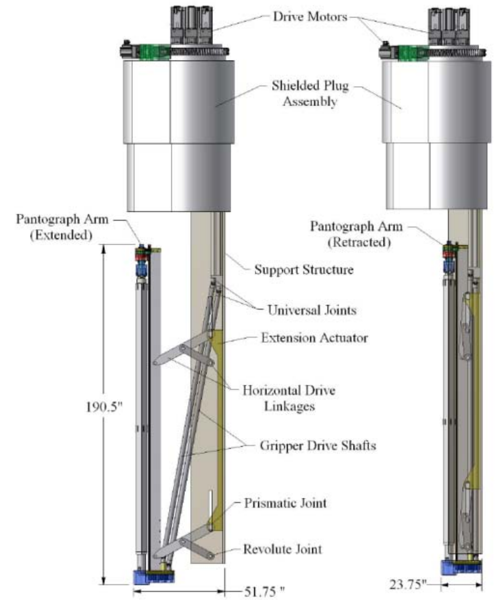
- **Areas previously investigated include:**
- **Impact of Advanced Materials – potential for stronger materials reducing plant commodity usage**
- **Impact of Increasing Core Outlet Temperature – increased power output due to increased efficiency**
- **Advanced System and Components include:**
  - Compact fuel handling mechanisms
  - Advanced Balance of Plant Systems
  - Vented Fuel
  - Ultra-Long-lived fast reactor cores
  - Integrated primary purification systems
  - Advanced heat exchanger technology options

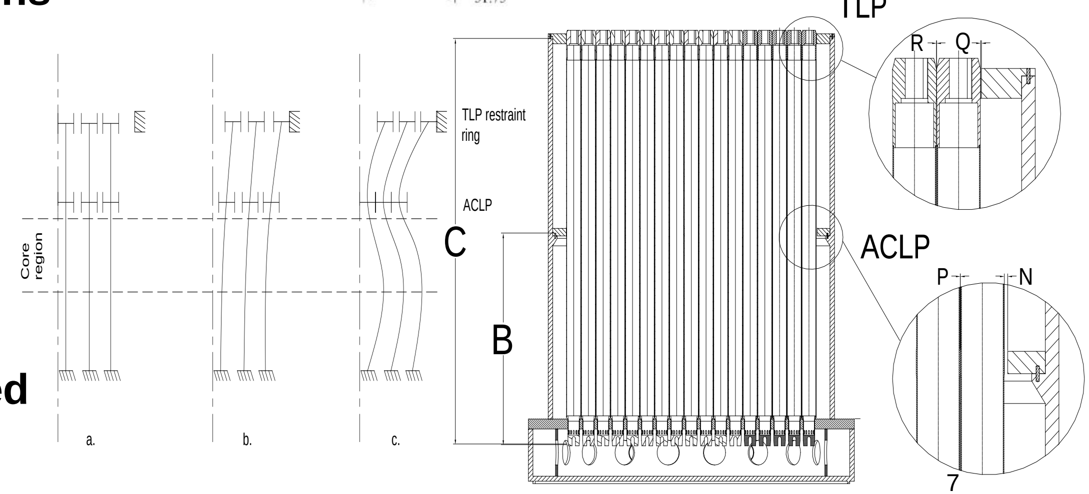


Structure	Parameter	Base	Advanced
Reactor vessel (RV)	Material	316SS	HT-UPS
	Thickness, mm	25.4	15.9
	Mass, kg	255,830	171,914
	Additional savings from IHX	0	-21,322
	Total RV mass, kg	255,830	150,592
Core support structure	Material	316SS	HT-UPS
	Thickness, mm	15.2	10.2
	Mass, kg	109,771	73,483
IHX	Material	304SS	NF616*
	Thickness (tube), mm	1.24	0.889
	IHX mass, kg	52,853	33,730
	Number of IHXs per plant	4	4
	Total IHX mass per plant, kg	211,414	134,920
Intermediate Heat Transport System (IHTS) Piping	Material	316SS	HT-UPS
	Thickness (hot leg/cold leg), mm	25.4/12.7	10.1/9.5
	Mass per loop, kg	53,210	27,344
	Number of loops per plant	4	4
	Total IHTS piping mass, kg	212,842	109,377
Steam generator (SG)	Material	2-1/4Cr-1Mo	NF616*
	Thickness (tube), mm	5.9	2.95
	SG mass, kg	236,009	122,509
	Number of SG's per plant	4	4
	Total SG mass per plant, kg	944,037	490,038
TOTAL MASS OF CONSIDERED STRUCTURES, kg		1,733,894	958,410
	Material savings, kg		775,484
	Material savings, %		44.7%

Fast Reactor Advanced Concept Studies (examples)

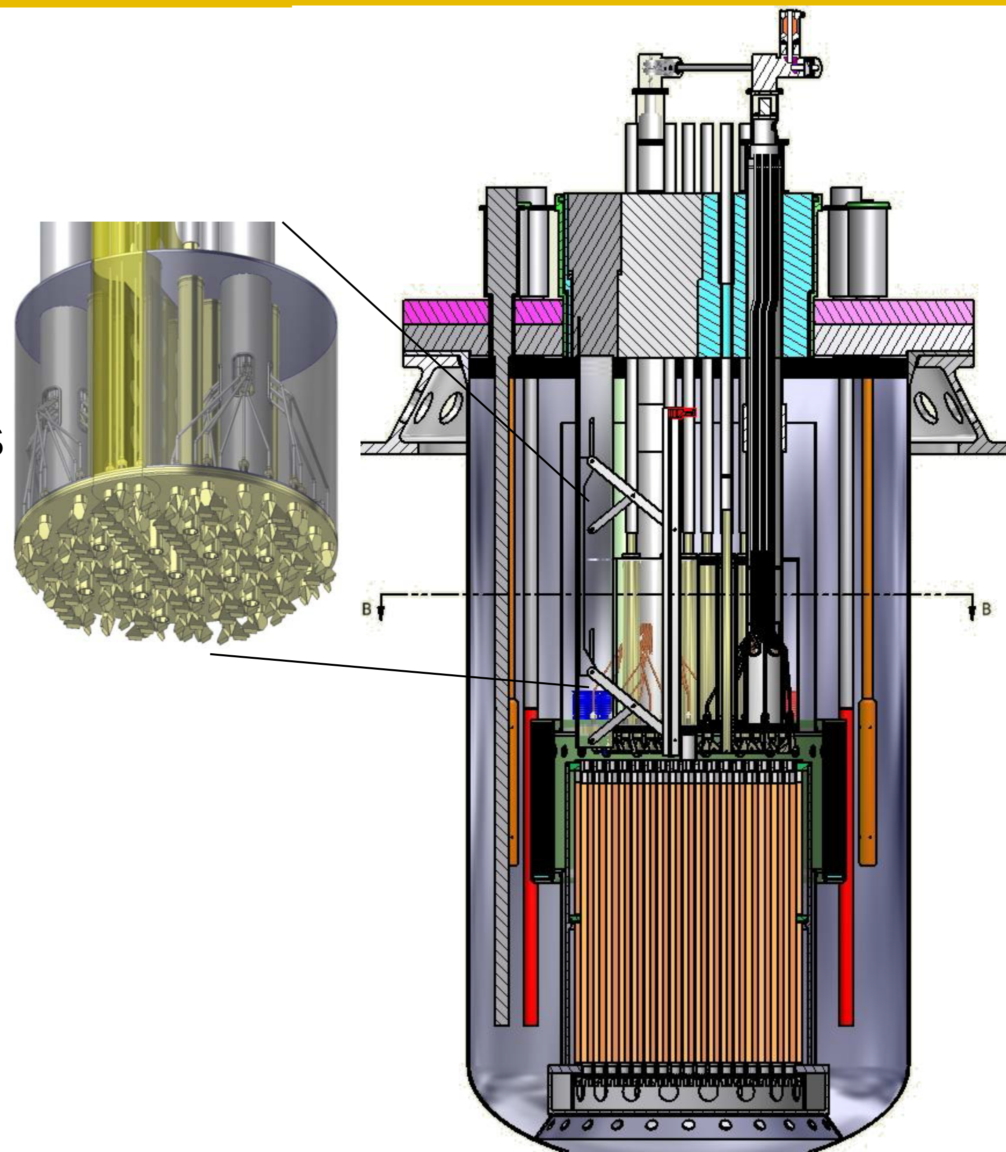
- **<u>FY11 and FY12 work focused on SMR (~100 MWe) concepts:</u> unique features include long-lived core and fuel shuffling strategies**
- **Developed compact fuel handling mechanism:**
  - Single rotating plug configuration
  - Pantograph design
  - Offset from center
- **Detailed analysis and design options for core restraint**
  - A key feature for inherent safety reactivity feedbacks
  - NUBOW bowing analysis code recovered and refined
  - Limited free bow design
- **AFR-100 safety analyses conducted**
  - Verify inherent safety in double fault transients





AFR-100 Upper Internal Structure

- **Upper Internal Structure**
  - Very complicated structure within the primary plant
  - Made from 316SS and clad with Alloy 718 for thermal fatigue resistance
  - Contains multiple plates of Alloy 718 at the bottom portion of the UIS
  - UIS is lifted by a lifting drive mechanism to clear some systems and components before and during rotation
  - UIS is keyed into the core barrel structure to prevent lateral movement during seismic events
  - Advanced Fuel Handling System is integrated with the UIS



Fast Reactor Advanced Concept Studies - Thorium fuelled AFR-100 core

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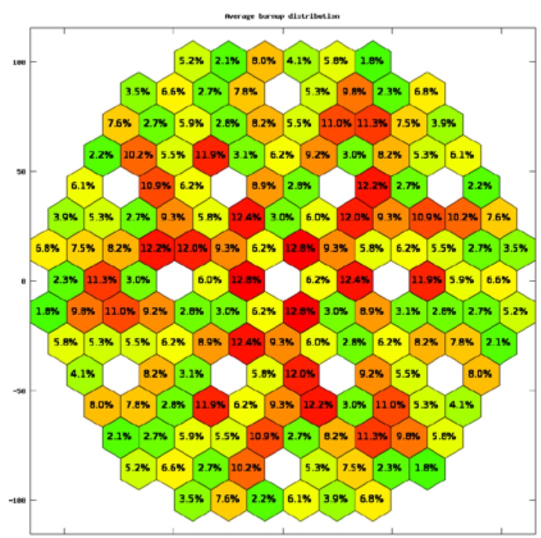
- **Purpose - The feasibility study of fuel changes from U-based fuel to Th-based fuel in a small SFR**
- **Various approaches with Th-TRU:**
  1) Conventional 4-batches operation with Th-TRU (18.6wt%). No U-Zr startup core.
  2) Progressive replacement of U-Zr assemblies with Th-TRU (14.4-22wt%). No equilibrium operation
  3) Progressive replacement of U-Zr assemblies with Th-TRU (18.6wt%). 4-batches equilibrium strategy
- **Different performance with various pros and cons (peak power; reactivity swing; discharge burnup…)**
- (Review still in progress with a report due in June 2012)

Characteristic	Unit	(1)	(2)	(3)
Average TRU wt%	wt%	18.60%	18.65%	18.60%
Burnup reactivity swing	%Δk/k	0.73	1.3	1.25
Average power density	W/cm^3		58.3	
Peak power density	W/cm^3	110.3	112.7	114.8
Radial power peaking factor	-	1.32	1.36	1.45
Average/Peak BU – U-Zr	%	n.a.	7.4%/ 11.9%	12%/ 22.2%
Average/Peak BU – Th-TRU	%	10.2%/ 16.2%	7.8%/ 17.4%	10.2%/ 16.2%



Burnup distribution at EOEC for (1)

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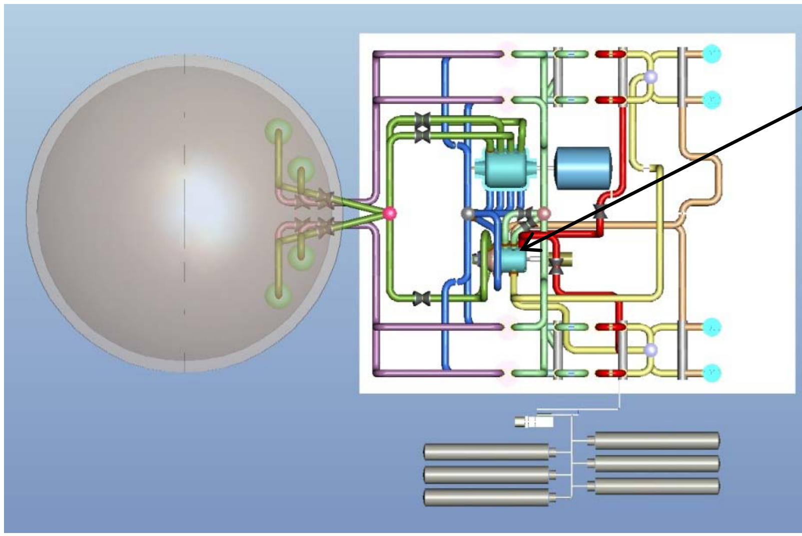
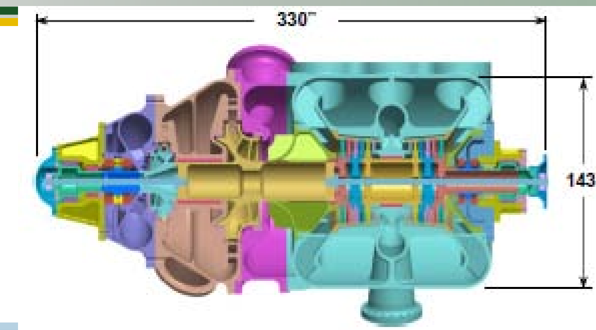
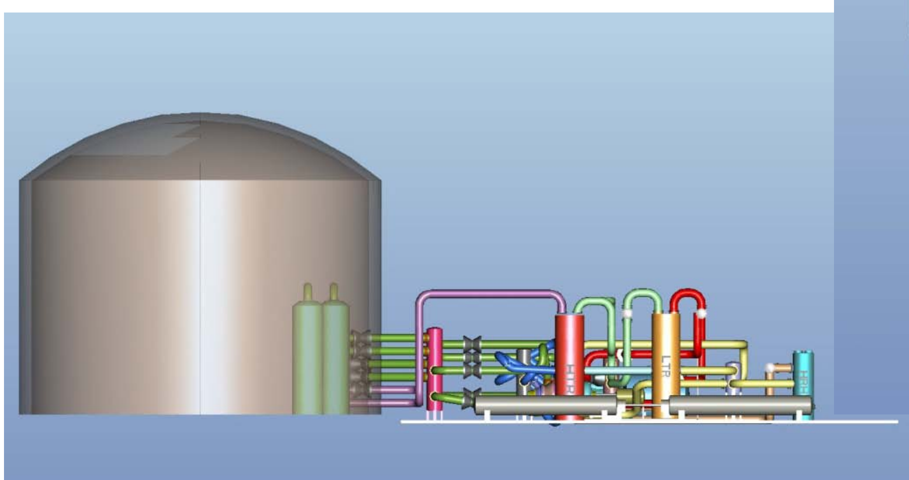
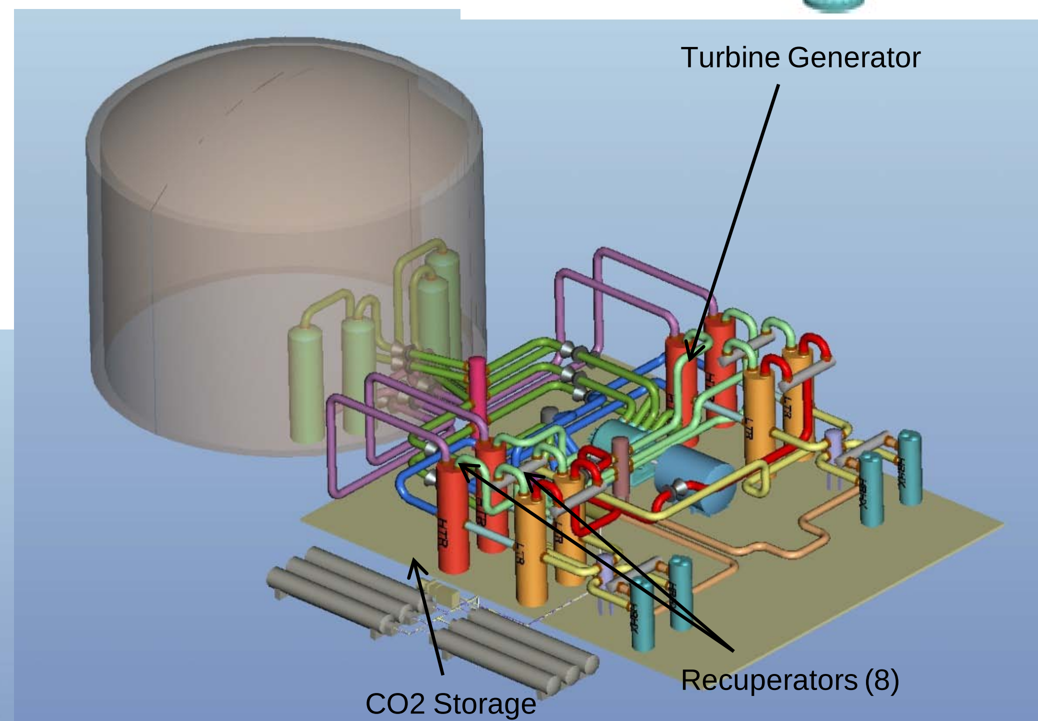
Supercritical CO_2 Cycle Coupled to an Advanced Liquid Metal Reactor



Compressor/Recompressor with turbine



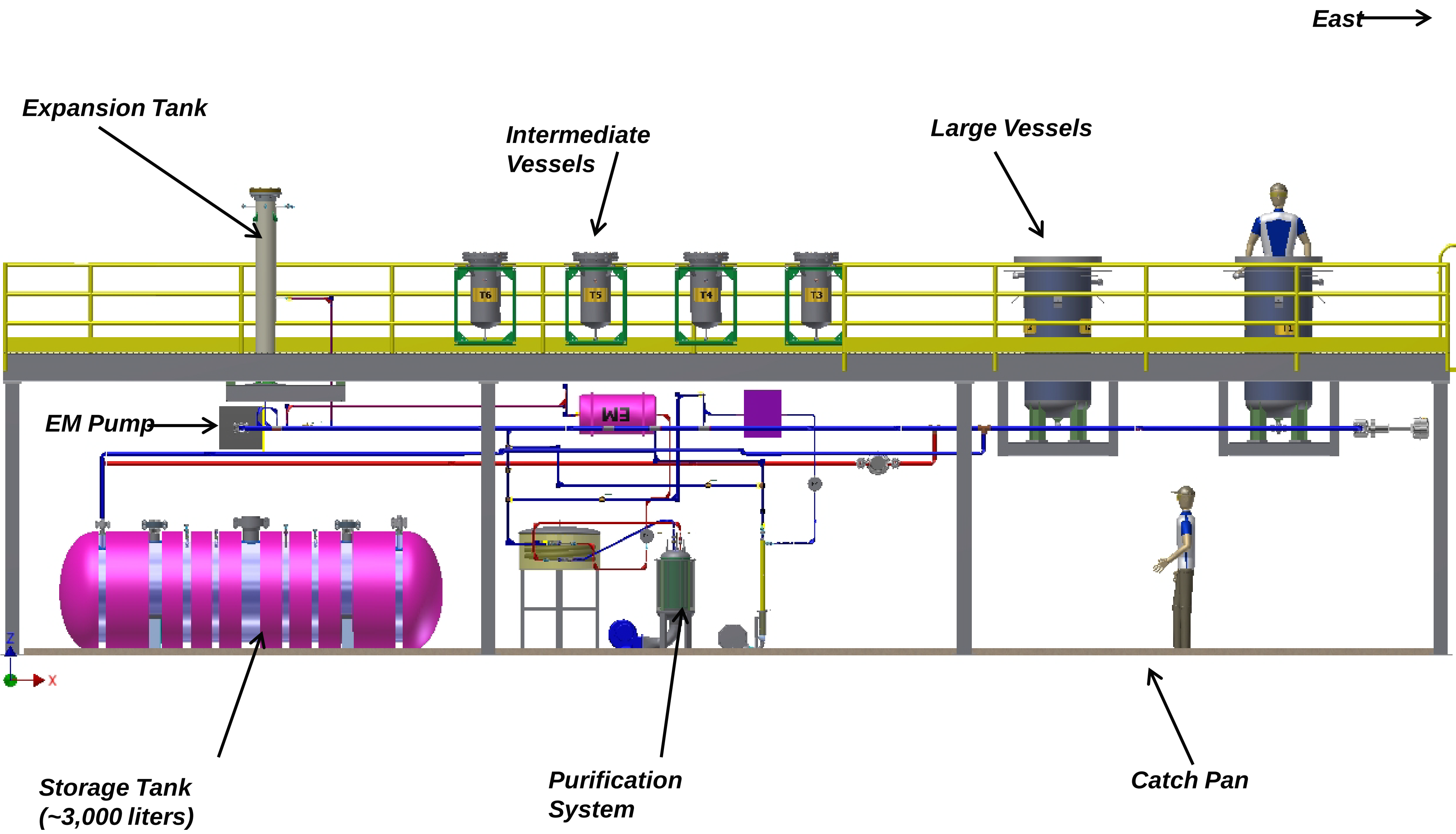




Mechanisms Engineering Test Loop (METL) Facility Purpose

- **To test small or intermediate scale advanced liquid metal components in sodium for the future of advanced fast reactor system development**
- **To develop and provide performance data of components used in sodium and reduce the risk of failures during reactor plant operation**
- **U.S. lacks the infrastructure to test liquid metal components**
- **This work supports the Trilateral work between U.S., France, and Japan and, of course, our own research.**

Elevation View of METL Facility in Building 308



Fast Reactor Safety and Licensing: Program Objectives

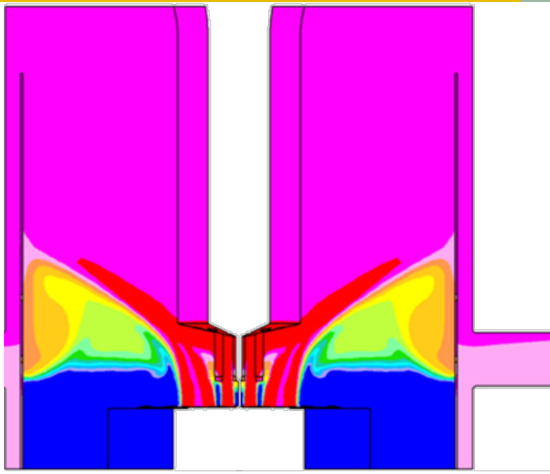
- Develop enhanced safety technologies for accident prevention and mitigation through science-based R&D
- Preserve and manage data, knowledge, and experience related to past U.S. DOE FR operations and tests
- Engage international community in bilateral or multilateral agreements in advanced reactor R&D
- Provide initial verification and validation basis (i.e. focus and direction) for emerging advanced modeling and simulation programs
- Start implementing the recommendations of “regulatory development plan” to close the FR licensing gaps identified by five expert panels

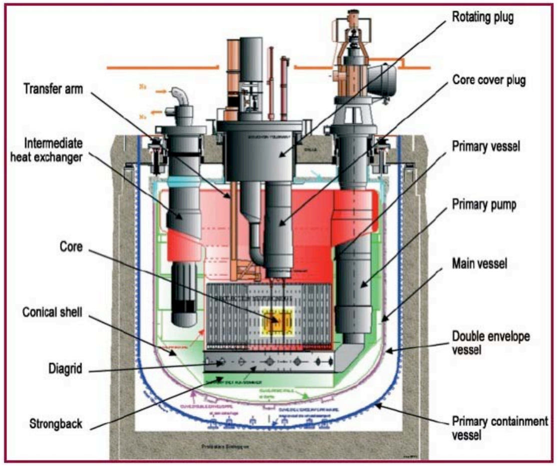
Fast Reactor Safety and Licensing: International Passive Safety Benchmarks

■ **Key Accomplishments to date**

- Completion of IAEA benchmarks for PHENIX end-of-life natural circulation test
  - *Final project report (IAEA Technical Document) is being finalized*

- Initiation of IAEA benchmarks for EBR-II Shutdown Heat Removal Tests for inherent safety demonstration
  - *Benchmark proposal was prepared and submitted to IAEA as a Coordinated Research Project*
  - *Kick-off research coordination meeting is scheduled at Argonne in June 2012*





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Fast Reactor Safety and Licensing: Regulatory Development Plan

- **If SFRs are to be a long term and stable component of the future US energy supply, development of the safety case and appropriate SFR licensing approaches will be essential**
  - Requires evaluation of the existing technology base, identifying where gaps for regulatory process exists, and developing a plan to perform the experimental and modeling work needed to close these gaps

A plan to address important SFR safety/regulatory gaps has been developed though multiple extensive experts' elicitations

DOE Labs	Universities	International Bodies

Results from previously conducted SFR gap analyses are used to rank the identified needs within the following areas

Sodium Fire Experiments and Modeling	Source Term Characterization	Fuels and Materials Research	Accident Sequences and Initiator Characterization	Computer Codes and Models

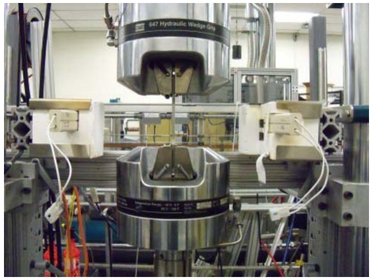
Creating a cumulative multi-lab plan led by SNL to

Prioritize the efforts	Identify the developmental time frames	Suggest facilities and organizations that can generate the needed information

Next steps on advanced materials development

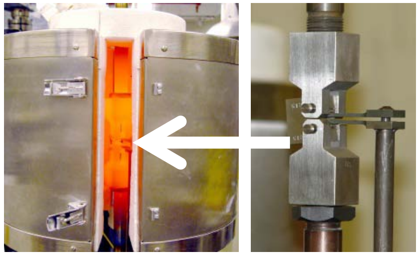
- Based on short-term tests performed on candidate alloys with different chemical compositions, recommendation on the compositions of one ferritic/martensitic alloy and one austenitic alloy that have significant performance improvement will be made in September 2012
- A two-year intermediate-term test program (FY13, 14) will be conducted to verify the expected performance improvement before initiating long-term effort to generate data for codification in ASME Boiler and Pressure Vessel Code, Section III - the nuclear section

Tests are being conducted on advanced materials


Tensile

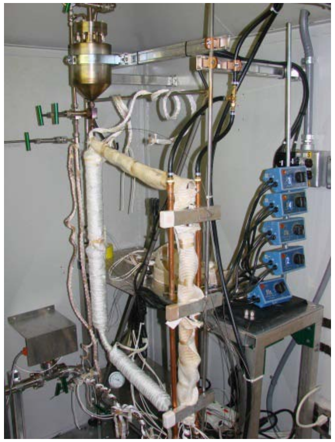

Creep Tests


Charpy Impact


Fracture Toughness


Creep-Fatigue

Sodium Compatibility Testing


Thermal Convection Loop


Forced Convection Loop

Generating needed data is challenging because of time required at temperature and in sodium environment

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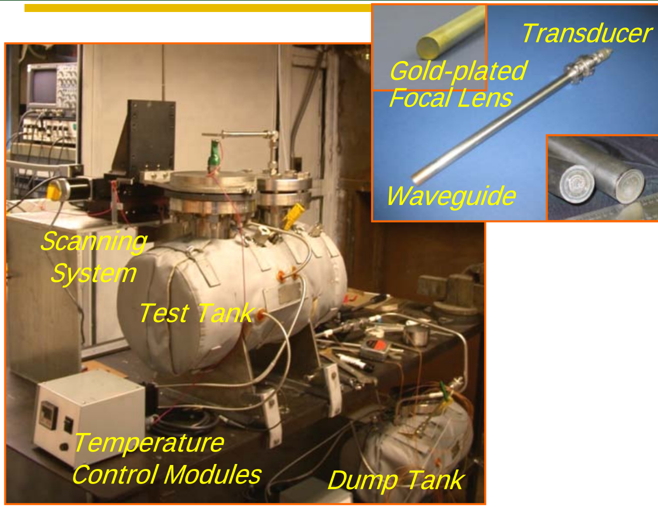
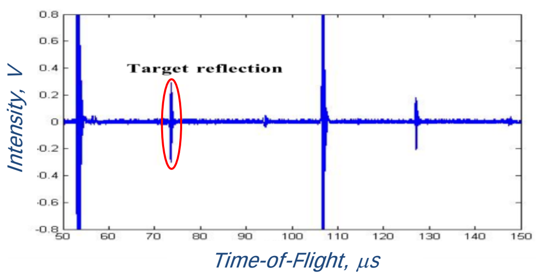
USV System Evaluation – Under Sodium Tests

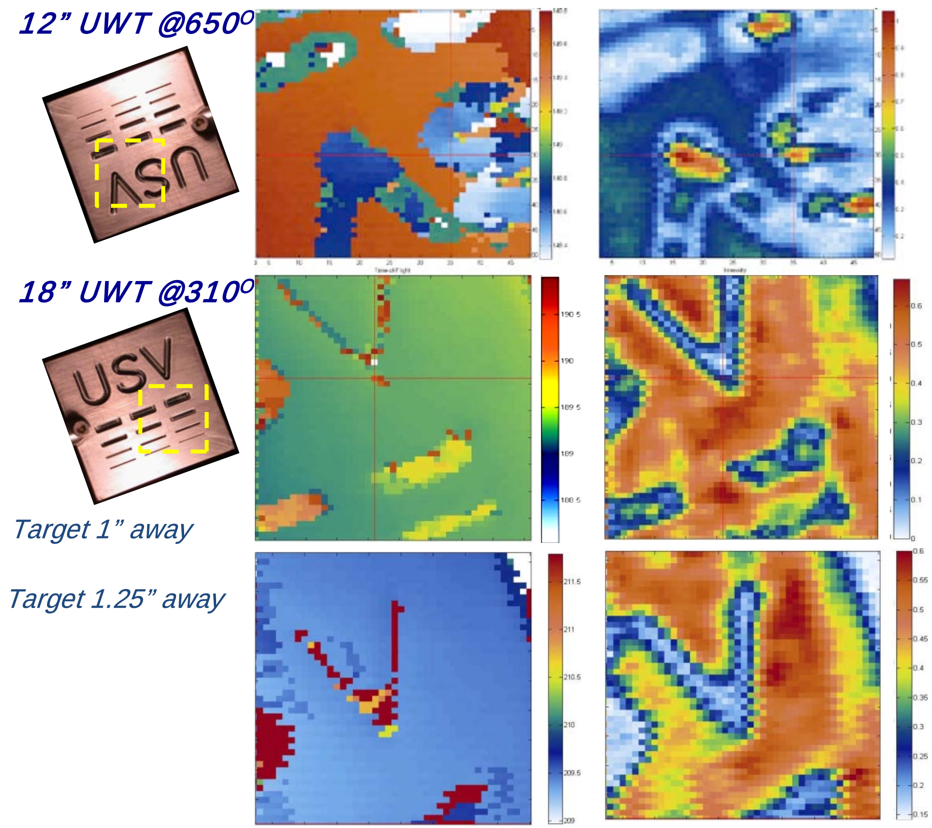


Argonne WGT Prototype (D=0.625", L=12")



Sodium Tests

Scanning Size: 1" x 1"; Resolution: 50 pixel/inch
Lateral Resolution: 1mm; Vertical Resolution 0.5mm



Advantages of Argonne UWT:

- ❑ *Reduce the background noise and spurious signal*
- ❑ *Minimize the waveguide attenuation*
- ❑ *Create a clear window to detect target reflection*
- ❑ *Maximize the signal to noise ratio*

FHRs as Future Primary Electricity and Heat Source

- **Large FHRs have transformational potential to provide lower cost, high efficiency, large scale electrical power**
  – May be cheaper than LWRs due to higher thermal efficiency and low-pressure, and passive safety
- **Small, modular FHRs can be cost effective, local process heat sources and/or electricity generators**
  – For hydrogen production or support domestic oil shale based gasoline prodution
- **FHRs have a high degree of inherent passive safety**
  – No requirement for offsite power or cooling water
  – Low-pressure primary and intermediate loops
- **Plant concept and technologies must be matured significantly before the potential for FHRs can be realized**
  – Lithium enrichment must be reindustrialized
  – Tritium extraction technology must be developed and demonstrated
  – Structural ceramics must become safety grade engineering material
  – Safety and licensing approach must be developed and demonstrated
  – Structured fuel manufacturing technology must be demonstrated

Concept Development Studies

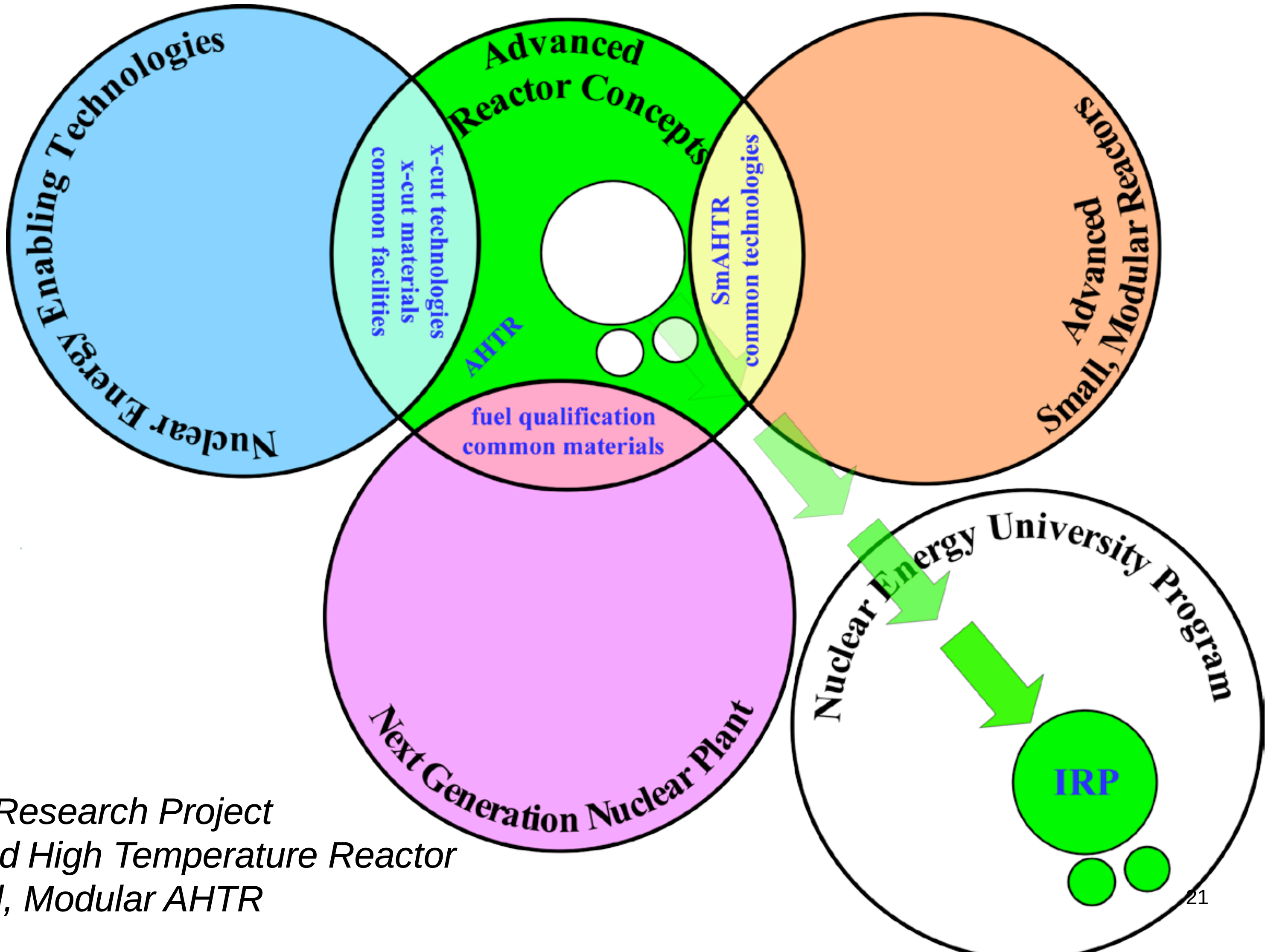
ARC FY11 work was focused initial FHR concept development

- **Identify the key R&D needs and challenges**
- **Pursue fundamental understanding of technical utilization of advanced technology options in integrated reactor system**
- **Evaluate broad range of technology options**

Current FHR technology areas:

- **Fluidic diode development**
- **Fuel handling mechanisms**
- **Safety & licensing**

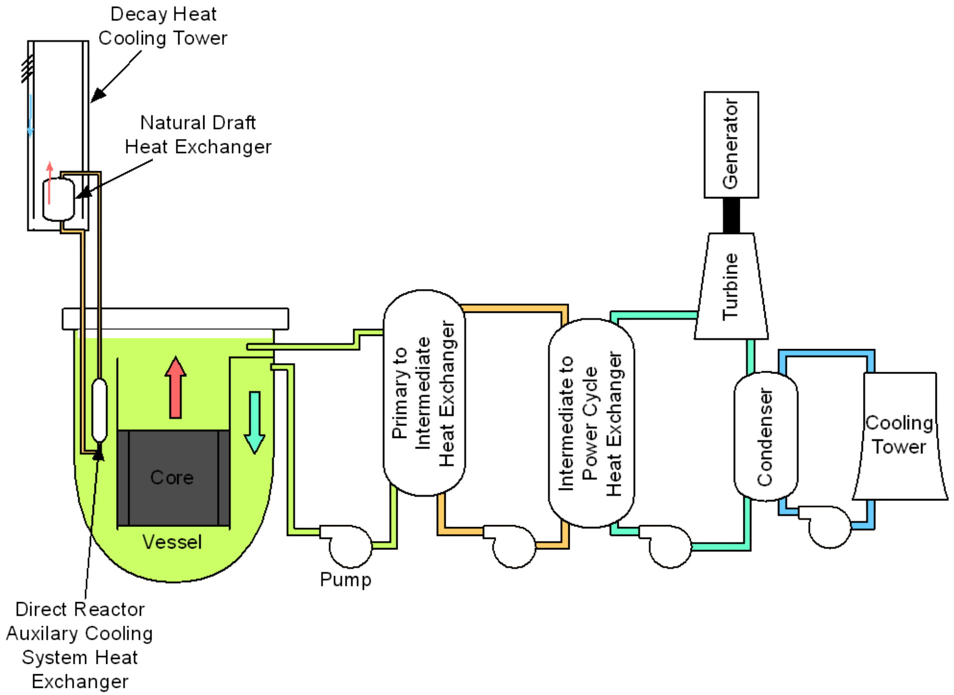
Advanced Reactor Concepts is the Integrating Organization for FHR Development



IRP = Integrated Research Project
AHTR = Advanced High Temperature Reactor
SmAHTR = Small, Modular AHTR

FHR is Progressing Towards a Preconceptual Design Level of Maturity

Both reactor and power plant systems are included in the modeling

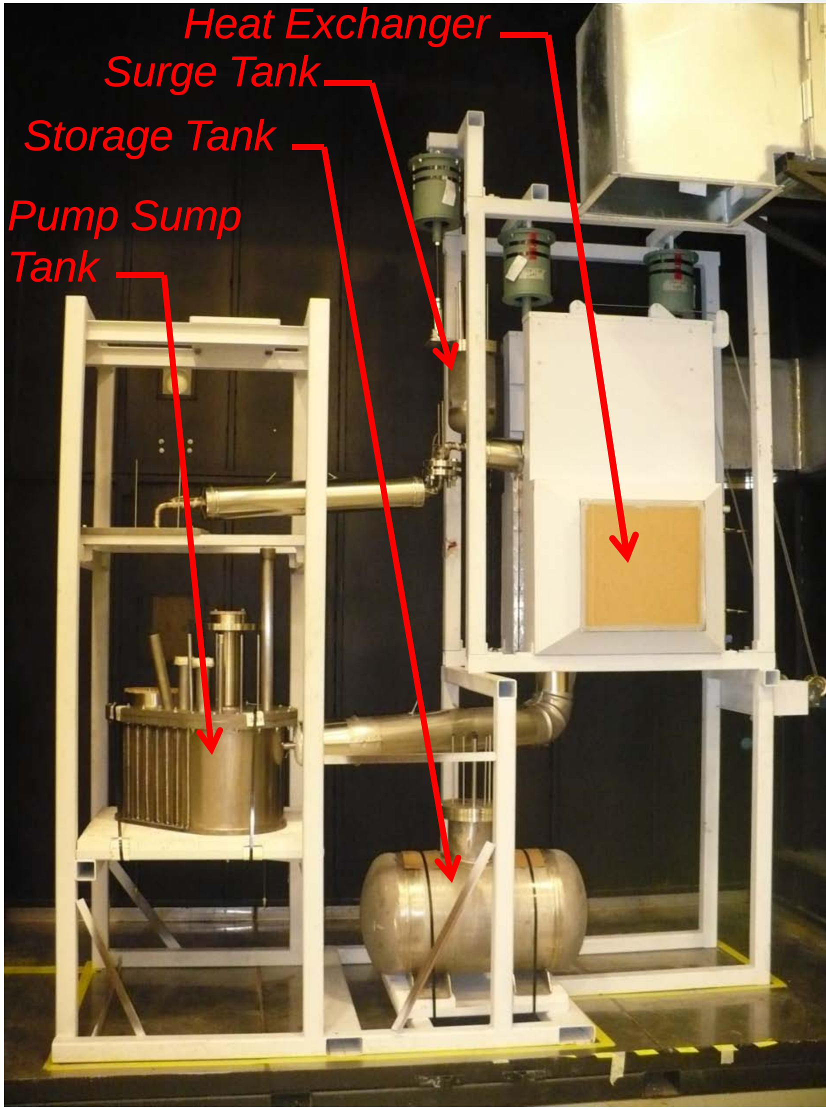


FHR Properties	
Thermal Power	3400 MW
Electrical Power	1500 MW
Top Plenum Temperature	700 °C
Coolant Return Temperature	650 °C
Number of loops	3
Primary Coolant	$2^{7}LiF\text{-}BeF_2$
Fuel	UCO TRISO
Uranium Enrichment	9%
Fuel Form	Plate Assemblies
Refueling	2 year batch 6 month

Providing Fluoride Salt to Czech Republic

- **Subdivide existing canister of $2^7LiF\text{-}BeF_2$ of into 75 kg aliquots**
  - Equipment installed
  - Final checkout underway
  - Large salt vessel installed March 30
  - Salt melt initiated by April 16
  - Salt transferred by April 20
  - Ready to ship by May 25

Versatile Liquid Salt Loop Under Construction To Help Develop High Temperature Salt Components



- **Experimental facility will include a salt purification system designed to remove moisture and oxides in the salt to minimize corrosion**
- **A fluidic diode (a leaky check valve with no moving parts) will be tested early in the experimental program**
  - Key decay heat removal component

- **Follow on testing will focus on scaled AHTR components such as:**
  - Fuel heat transfer testing
  - Improved pump designs
  - Salt-to-salt or salt-to-gas heat exchanger
  - Instrumentation
  - Refueling components

S-CO2 Brayton Cycle

- *Recent focus has been to:*
  - *Complete upgrades. and test the 1 MW system at the contractor facility. in Colorado*
  - *Transport the system from the contractor facility to Sandia Albuquerque.*
  - *Perform commissioning tests on the system to verify functionality.*
  - *Open the Nuclear Technology Users Facility (NTUF) for commercial component demonstration testing.*

International Collaborations

SFR Generation IV SFR Research

6 member nations

Topics

- System Integration and Assessment
- Safety and Operations
- Advanced Fuel
- Component Design and Balance-of-Plant
- Global Actinide Cycle International Dem

Trilateral (US-FR-JAP)

- **Steering & Executive Committee Meeting in October 2010**
- **Extensive collaborative R&D scope included in Specific Topic of Collaboration (STC) summaries**
  - Intent is to focus collaboration with FR-JAP in trilateral
- **For each STC, work plans were generated, Fall, 2011**
- **Executive Committee Meeting, November 22, 2011**
- **12 topic areas of cooperation are agreed to and have work plans developed**
- **HOWEVER, a formal agreement for the trilateral collaboration is yet to be established**
  - Until then, limited to information sharing under existing MOU

Advancing the nuclear fuel cycle requires improvements in basic nuclear data

- **Nuclear data plays a fundamental role in the advanced simulation and design calculations performed in across the nuclear fuel cycle**

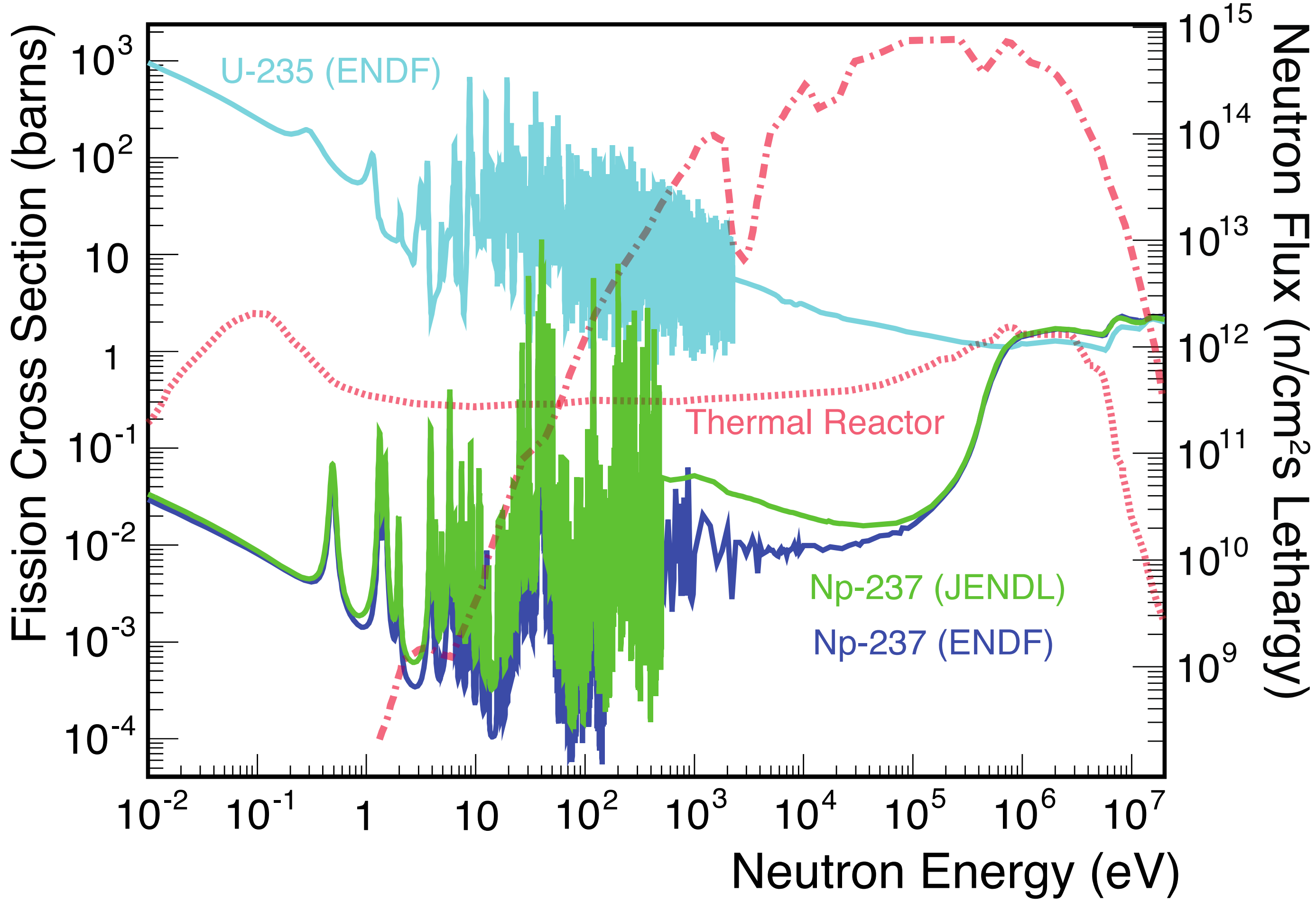
  Most important
  - Reactor core performance and fuel design , especially in minor actinide burning fast reactors
  - Criticality safety

  - **Next Important**
  - Shielding
  - Material damage in structures
  - Decay heat at reactor shut-down
  - Decay heat in the repository
  - Mass flow in the fuel cycle

There are broad needs for nuclear physics in the advanced fuel cycle.

Nuclear Data Uncertainties

Fission Cross Sections and Fluxes vs Energy



Advanced Reactor Concepts (ARC) Summary of R&D Scope

- **Crosscutting R&D with potential benefits to many concepts:**
  - *Energy Conversion*
  - *Nuclear Data*
- **Address key R&D needs for fuel cycle fast reactors and high temperature molten-salt reactors**
  - *R&D guided by Concept Development Studies*
  - *Safety*
  - *Materials*
  - *Coolant Control and Chemistry*
  - *Inspection and Maintenance Technology*
- **International collaboration is important for a science-based approach to advanced reactor R&D**

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Backup

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Advanced Reactor Concepts (ARC) Program Accomplishments

1. Completed the 2nd phase (520 kW_{th}) of supercritical CO_2 Brayton cycle (S-CO_2) tests and finished construction of the 3rd phase (780 kW_{th})
2. Under Sodium Viewing (USV)—Design completed for high-temperature ultrasonic linear array. Currently proceeding with 6-element and then 24-element units.
3. The Regulatory Licensing Safety Gap Analysis panels were completed; and the prioritized plan for safety and licensing tasks will be completed in FY12
4. Modified the liquid metal plugging loop to allow temperature control for prototypic testing; procured and assembled the sodium-CO_2 testing apparatus
5. Completed design of a Mechanisms Engineering Facility that supports testing of liquid metal reactor components and mechanisms
6. The safety analyses of IAEA benchmarks for MONJU natural circulation cooling experiment and PHENIX end-of-life transient tests was completed
7. Evaluated system options for innovative FHR concept (e.g., on-line refueling variants, power cycle, secondary shutdown mechanisms)
8. Continued the assembly of a fluoride salt test loop for testing of FHR materials, components, heat transfer, and safety capabilities